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**DTRA-TR-12-048**

# TECHNICAL REPORT

## **Comparison of Radiation Dose Studies of the 2011 Fukushima Nuclear Accident Prepared by the World Health Organization and the U.S. Department of Defense**

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**November 2012**

Prepared by:

Operation Tomodachi Registry,  
Dose Assessment and Recording Working Group

For:

Assistant Secretary of Defense for Health Affairs



<b>REPORT DOCUMENTATION PAGE</b>				<b>Form Approved OMB No. 0704-0188</b>	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</small> <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
<b>1. REPORT DATE (DD-MM-YYYY)</b> 10-12-2012		<b>2. REPORT TYPE</b> Technical report		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b>  Comparison of Radiation Dose Studies of the 2011 Fukushima Nuclear Accident Prepared by the World Health Organization and the U.S. Department of Defense				<b>5a. CONTRACT NUMBER</b> HDTRA1-07-C-0015	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
				<b>5d. PROJECT NUMBER</b>	
<b>6. AUTHOR(S)</b>  Chehata, Mondher				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Science Applications International Corporation (SAIC), McLean, VA				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  DTRA-TR-12-048	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Nuclear Technology Department, Attn: Dr. Paul Blake Defense Threat Reduction Agency 8725 John J. Kingman Road, Mail Stop 6201 Fort Belvoir, VA 22060-6201				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> DTRA J9-NTSN	
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>	
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> DISTRIBUTION A. Approved for public release: distribution is unlimited.					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> The earthquake and the tsunami that occurred in Japan on March 11, 2011 led to releases of radioactive materials from the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station into the environment. This report compares data, assumptions, exposure pathways, and estimation methods used in the two radiation dose assessments prepared by the World Health Organization and the United States Department of Defense. The range of doses estimated by the two groups are compared and found to be generally in agreement at the locations covered by both studies.					
<b>15. SUBJECT TERMS</b> Operation Tomodachi, Fukushima, Radiation Dose Assessment, Department of Defense, World Health Organization, Japan, Earthquake, Tsunami					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b> Dr. Paul K. Blake
a. REPORT	b. ABSTRACT	c. THIS PAGE	U	13	<b>19b. TELEPHONE NUMBER (Include area code )</b> 703 767-3384
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# UNIT CONVERSION TABLE

## Conversion factors for U.S. customary to metric (SI) units of measurement

U.S. Customary Units	Multiply by	To Get Metric (SI) Units
<b>Length/Area/Volume</b>		
inch (in)	$2.54 \times 10^{-2}$	meter (m)
foot (ft)	$3.048 \times 10^{-1}$	meter (m)
mile (mi, international)	$1.609\,344 \times 10^3$	meter (m)
micron ( $\mu$ )	$1 \times 10^{-6}$	meter (m)
angstrom ( $\text{\AA}$ )	$1 \times 10^{-10}$	meter (m)
barn (b)	$1 \times 10^{-28}$	meter <sup>2</sup> (m <sup>2</sup> )
gallon (gal, U.S. liquid)	$3.785\,412 \times 10^{-3}$	meter <sup>3</sup> (m <sup>3</sup> )
gallon (gal, U.S. liquid)	3.785 412	liter (L)
<b>Mass/Density/Force</b>		
pound (lb)	$4.535\,924 \times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	$1.660\,539 \times 10^{-27}$	kilogram (kg)
pound-mass foot <sup>-3</sup> (lb ft <sup>-3</sup> )	$1.601\,846 \times 10^1$	kilogram m <sup>-3</sup> (kg m <sup>-3</sup> )
pound-mass-foot <sup>2</sup> (lb ft <sup>2</sup> )	$4.214\,011 \times 10^{-2}$	kilogram-meter <sup>2</sup> (kg m <sup>2</sup> )
pound-force (lbf avoirdupois)	4.448 222	newton (N)
pound-force inch (lbf in)	$1.129\,848 \times 10^{-1}$	newton-meter (N m)
pound-force inch <sup>-1</sup> (lbf in <sup>-1</sup> )	$1.751\,268 \times 10^2$	newton-meter <sup>-1</sup> (N m <sup>-1</sup> )
<b>Energy/Power</b>		
electronvolt (eV)	$1.602\,177 \times 10^{-19}$	joule (J)
erg	$1 \times 10^{-7}$	joule (J)
kilotons (kT) (TNT equivalent)	4.184	terajoule (TJ)
British thermal unit (Btu) (thermochemical)	$1.054\,350 \times 10^3$	joule (J)
foot-pound-force (ft lbf)	1.355 818	joule (J)
calorie (cal) (thermochemical)	4.184	joule (J)
joule second <sup>-1</sup> (J s <sup>-1</sup> )	1	watt (W)
<b>Pressure</b>		
kip inch <sup>-2</sup> (ksi)	$6.894\,757 \times 10^3$	kilopascal (kPa)
atmosphere (atm)	$1.013\,250 \times 10^2$	kilopascal (kPa)
bar	$1 \times 10^2$	kilopascal (kPa)
torr (Torr)	$1.333\,224 \times 10^{-1}$	kilopascal (kPa)
pound-force inch <sup>-2</sup> (psi)	6.894 757	kilopascal (kPa)
<b>Angle/Temperature/Time</b>		
hour (h)	3600	second (s)
degree of arc ( $^{\circ}$ )	$1.745\,329 \times 10^{-2}$	radian (rad)
degree Fahrenheit ( $^{\circ}\text{F}$ )	$[\text{T}(^{\circ}\text{F}) - 32]/1.8$	degree Celsius ( $^{\circ}\text{C}$ )
degree Fahrenheit ( $^{\circ}\text{F}$ )	$[\text{T}(^{\circ}\text{F}) + 459.67]/1.8$	kelvin (K)
<b>Radiation</b>		
curie (Ci)	$3.7 \times 10^{10}$	becquerel (Bq)*
joule kilogram <sup>-1</sup> (J kg <sup>-1</sup> ) (absorbed dose)	1	gray (Gy) <sup>†</sup>
radiation absorbed dose (rad)	$1 \times 10^{-2}$	gray (Gy) <sup>†</sup>
roentgen equivalent man (rem)	$1 \times 10^{-2}$	sievert (Sv) <sup>‡</sup>

\* Becquerel (Bq) is the special name for the SI unit of radioactivity (1 Bq = s<sup>-1</sup>).

<sup>†</sup> Gray (Gy) is the special name for the SI unit of absorbed dose (1 Gy = 1 J kg<sup>-1</sup>).

<sup>‡</sup> Sievert (Sv) is the special name for the SI unit of dose equivalent (1 Sv = 1 J kg<sup>-1</sup>).



**DTRA-TR-12-048: Comparison of Radiation Dose Studies of the 2011 Fukushima Nuclear Accident Prepared by the World Health Organization and the U.S. Department of Defense**

## **Table of Contents**

1.	Introduction.....	2
2.	The World Health Organization Dose Assessment .....	2
3.	The Department of Defense Dose Assessment .....	3
4.	Comparison of Major Factors of the WHO and DOD Dose Assessments .....	3
5.	Summary and Conclusion of the Dose Comparison .....	4
6.	References .....	5

## **List of Tables**

Table 1.	Comparison of main characteristics of the WHO and DOD dose assessments.....	6
Table 2.	Summary comparison of WHO and DOD doses .....	10



## **1. Introduction**

The earthquake and the tsunami that occurred in Japan on March 11, 2011 led to releases of radioactive materials into the environment from the Tokyo Electric Power Company's Fukushima Daiichi nuclear power station (FDNPS). Within weeks, radioactive materials dispersed and deposited across Japan and around the world. This report compares and contrasts the approaches and assumptions used in two comprehensive radiation dose assessment studies published in 2012 by the World Health Organization (WHO) and the United States Department of Defense (DOD). This comparison was driven by the need to present the methods and data used by two independent groups and to evaluate how well the results match for locations covered by the two studies.

In May 2012, the WHO published a report "Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami" (WHO, 2012). The assessment used data collected and made publicly available by the Government of Japan (GOJ) up to mid-September 2011 to assess doses inside and outside Japan. The WHO dose assessment includes exposures that occurred during the first year following the accident. The exposures to radiation for the period mid-September 2011 to March 11, 2012 were based on predicted behavior of Cs-134 and Cs-137 deposited on ground surfaces, because these two radionuclides are the only ones released to the environment with sufficiently long half-lives and residual activity. The work relied on the contribution of more than 30 scientists with participation of experts from the Food and Agriculture Organization of the United Nations, the International Atomic Energy Agency, and the International Agency for Research on Cancer as members of the panel. In addition, representatives of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and GOJ participated as observers.

The DOD initiated Operation Tomodachi immediately after the accident to provide humanitarian assistance and disaster relief to Japan. It subsequently established the Dose Assessment and Recording Working Group (DARWG) within a few months after the FDNPS nuclear accident to carry out radiation dose assessments for military personnel and other DOD-affiliated persons who were in Japan during the 60-day period from March 12 to May 11, 2011. The DOD/DARWG published its findings in a September 2012 report "Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi" (Cassata et al., 2012).

## **2. The World Health Organization Dose Assessment**

Preliminary dose estimates were developed for the general public both in Japan and the rest of the world. This radiation dose assessment forms one part of the overall health risk assessment being carried out by the WHO on the global impact of the accident at the FDNPS. The assessment will be used by the WHO Health Risk Assessment Expert Group to estimate the health risks incurred by different populations. A report on risk assessment is expected to be published in 2013.

The WHO dose estimates were based on measurements of radioactivity in the air, soil, drinking water and food supplies, which resulted from the accident. The doses are provided in order-of-magnitude dose bands, with decreased band width at the higher levels of the estimated



doses. The presentation of doses to greater levels of numerical accuracy was considered by the study panel to be inappropriate for this report given the un-quantified uncertainties of the assessment and its preliminary nature. However, the calculated values for the different scenarios were provided to the Health Risk Assessment Expert Group for use in the risk assessment phase.

### **3. The Department of Defense Dose Assessment**

The DOD dose assessment that the DARWG prepared represents one part of a process to estimate radiation doses and health risks to potentially exposed populations (PEP) that form the population of interest (POI). The POI is composed of DOD-affiliated individuals who were present in or around Japan (shore-based, ship-based and air crews) during the 60-day period following the accident at the FDNPS. The dose assessments being completed by DOD form the technical basis for the Operation Tomodachi Registry (OTR). The shore-based individuals constitute the bulk of the POI. The comparison in this report only concerns the doses evaluated for this group. The dose assessment for ship-based individuals and air crews is currently underway. Also, a radiation dose assessment report for embryo/fetus and breast-fed infants is being evaluated separately as of the time of the publication of this report.

The DOD dose assessment is based on measured environmental data such as external photon radiation dose rates and measured concentrations of radioactive materials in air, water, and soil. The approach used by DOD to estimate doses is based on standard dose calculation methods and input parameters published by the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), the U.S. Environmental Protection Agency (EPA) and other peer-reviewed sources. Also, the DARWG relied on guidance and standardized procedures from U.S. government programs with a long history of performing radiation dose assessments, such as the Nuclear Test Personnel Review (NTPR) Program (DTRA, 2010).

### **4. Comparison of Major Factors of the WHO and DOD Dose Assessments**

Table 1 compares the methods, data, and other characteristics used in the WHO and DOD radiation dose assessments. It also gives major assumptions and basis for the dose estimation methods. Table 2 compares the range of doses estimated by the two groups.

Both the WHO and DOD assessments relied as much as possible on the best available data. WHO data sources were mainly the GOJ, international organizations, such as International Atomic Energy Agency (IAEA) and the International Food Safety Authorities Network (INFOSAN), as well as national health and academic institutions. The DOD assessment used data mainly from GOJ, DOD and the U.S. Department of Energy (DOE). The timeframes for the assessments were one year and 60 days after the accident for the WHO and DOD, respectively. Both assessments considered total effective doses and total equivalent doses to the thyroid. The DOD estimated internal doses from the inhalation of radionuclides in the air, ingestion of tap water, and incidental ingestion of soil and dust. The WHO assessment did not include the soil and dust pathway, but it added a dietary exposure from the ingestion of local food. Most DOD-



affiliated individuals were not eating food from local supplies and a case-by-case evaluation is recommended for persons who report having consumed food from non-DOD sources.

The two groups attempted to estimate radiation doses using highly conservative but realistic assumptions that imply that the results are bounding or “high-sided.” This means that if more accurate input parameter values were used, the doses would be smaller. However, the WHO report states that “while estimated doses are presented mostly in order-of-magnitude dose bands of characteristic individual doses for each region considered, it cannot be expected that doses to all individuals within each region will necessarily lie within the order-of-magnitude dose bands presented” (WHO, 2012). On the other hand, DOD is carrying out a separate assessment of uncertainty to further determine whether its estimated doses are upper bounds, defined as at least equal to the 95<sup>th</sup> percentile dose calculated by probabilistic analysis. Preliminary results for four selected cohorts and locations indicate that the dose estimates in the DOD assessment are higher than the 95<sup>th</sup> percentile estimates. This separate ongoing probabilistic analysis of doses and related uncertainties is expected for publication in early 2013 (Chehata et al., 2013).

In addition to published environmental monitoring data, the two assessments relied on information found in the literature to develop assumptions about physiological parameters and living habits, which allowed the calculation of dose estimates for a range of scenarios, age groups and physical activity levels. The WHO results were reported as order-of-magnitude dose bands for wide geographical areas and for adults and two age groups for children. The DARWG-calculated doses are specified for 13 DOD on-shore locations; children in five age groups, adults, and humanitarian workers; four levels of physical activity; and four categories of presence indoors (0 to 24 hours per day).

In the WHO assessment, external doses were calculated based on ground deposition radiation measurements for the ground shine component, and on atmospheric transport modeling for the cloud shine component. The DOD external doses were based on ground-level exposure rate measurements. For the inhalation doses, the WHO employed atmospheric transport modeling based on Japanese source term estimates and surface activity of ground-deposited contamination while DOD used air sampling data.

## **5. Summary and Conclusion of the Dose Comparison**

*The results of the two assessments (Table 2) show that the dose estimates are generally in agreement for relevant locations and given the scope of each study.* The scope parameters include geographical areas considered, age groups, assumptions about the scenarios of exposure, time frame and other factors. The comparison of the dose results includes only the prefectures nearest Fukushima prefecture and the areas in the rest of Japan. These are considered relevant to both studies. For these areas, the total effective doses are estimated to be between 0.01 and 1 rem (0.1 to 10 mSv) for the WHO assessment. They are between 0.002 to 0.16 rem (0.02 to 1.6 mSv) for DOD for all age groups and locations using the assumption of the highest-exposure scenarios (highest physical activity and no time spent indoors.) For the thyroid, the total equivalent doses ranged from 0.1 to 1 rem (1 to 10 mSv) for the WHO assessment for all age groups, for all locations in prefectures neighboring Fukushima Prefecture, and the prefectures in the rest of



Japan, excluding Fukushima Prefecture itself. For all DOD locations assessed, the thyroid doses ranged from 0.007 to 1.2 rem (0.07 to 12 mSv) for the most exposed adults, and 0.008 to 2.7 rem (0.08 to 27 mSv) for the most exposed children, the higher dose being for 1–2 year-old children who would be assigned the dose for the Hyakuri Air Base location in Ibaraki Prefecture south of Fukushima.

## 6. References

- Cassata, J., Falo, G., Rademacher, S., Alleman, L., Rosser, C., Dunavant, J., Case, D., Blake, P., 2012. *Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi*. DTRA-TR-12-001, Defense Threat Reduction Agency, Fort Belvoir, VA. September 31.
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- DTRA (Defense Threat Reduction Agency), 2010. *NTPR Standard Operating Procedures Manual, Revision 1.3/1.3a*. Defense Threat Reduction Agency, Fort Belvoir, VA. March 31.
- WHO (World Health Organization), 2012. *Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami*. World Health Organization, Geneva, Switzerland. May.



**Table 1. Comparison of main characteristics of the WHO and DOD dose assessments**

<b>Characteristic/ Parameter</b>	<b>World Health Organization (WHO)</b>	<b>Department of Defense (DOD)</b>
Main sources of data	MEXT/DOE, IAEA, Comprehensive Nuclear-Test-Ban Organization (CTBTO), EPA, International Food Safety Authorities Network (INFOSAN)	MEXT, DOE, DOD, EPA, IAEA.
<b>SCOPE OF ASSESSMENTS</b>		
Population of interest	General public (Japan and worldwide)	All DOD-affiliated persons
Time frame	1 year following accident	60 days following accident
Geographical locations	Fukushima prefecture most affected locations excluding area within 20 km radius Rest of Fukushima prefecture (less affected locations) Prefectures nearest to Fukushima Rest of Japan Neighboring countries Rest of the world	Japan (onshore locations) where DOD-affiliated persons could have been present 20 km (J-Village) to 1130 km (Sasebo NB) (12 miles and 702 miles, respectively): Prefectures near Fukushima prefecture. Other distant prefectures equivalent to “Rest of Japan” in WHO assessment.
Age groups	Adult: > 17 years Children: 10 years Children: 1 year	Humanitarian adult Adult: > 17 years Children: 0 to 1 year 1 to 2 years 2 to 7 years 7 to 12 years 12 to 17 years
Embryo, fetus and breastfed infant	Doses were not calculated explicitly; presumed the same as mother’s or child	Being evaluated separately (work in progress as of the time of the publication of this report)
Assessment type	Total effective dose (whole body external plus internal effective doses) Total equivalent dose to the thyroid (whole body external plus committed equivalent dose to the thyroid)	Total effective dose (whole body external plus internal effective doses). Total equivalent dose to the thyroid (whole body external plus committed equivalent dose to the thyroid).



Characteristic/ Parameter	World Health Organization (WHO)	Department of Defense (DOD)
<b>ENVIRONMENTAL ASSUMPTIONS AND PARAMETERS</b>		
Radiation sources (external)	Ground shine, cloud shine Doses were calculated based on ground deposition measurements for the ground shine component, and on atmospheric transport modeling for the cloud shine component.	Combined ground shine and cloud shine. Doses based on ground-level exposure rate measurements.
Time indoors (h/day)	16	Humanitarian: 0 Adult: 0 to 24 Children: 0 to 24
Protection factor while indoors from external radiation	2.5	2.0
Radiation sources (internal)	Inhalation of radioactive materials in cloud Ingestion of food and tap water	Inhalation of all airborne radioactive materials Ingestion of tap water and contaminated dust and soil
Inhalation rate (m <sup>3</sup> /d)	Adult: 22 Child 10 years: 15 Child 1 year: 5	Humanitarian: 32 Adult: 15 to 30 Children (1–15 years): 4.5 to 17 Infant 6 months: 4 to 9 Depends on physical activity level for each age group.
Indoors reduction in air concentrations	0.0	Aerosols: 0.5 Gases: 0.0
Iodine Gas/Aerosol	1.0	2.6
Gaseous iodine form	100 % elemental	2/3 organic, 1/3 elemental, based on DOE air activity measurements.
Air concentration input for inhalation intake	Atmospheric transport modeling based on Japanese source term estimates and ground deposition (surface activity)	Based on air sampling data.



Characteristic/ Parameter	World Health Organization (WHO)	Department of Defense (DOD)
Radionuclide mixture for inhalation intake	<p>Radionuclide mixture based on information from Japanese authorities.</p> <p>Some radionuclides appear to have relationships to Cs-137 that are significantly different than values obtained by air sampling at Yokota Air Base.</p> <p>The authors recognize that I-131 to Cs-137 ratios south of the plant may be significantly higher than those used in the report, which is definitely the case, based on air sampling data at Yokota AB. The authors did not use air sampling data. This would result in underestimated thyroid organ doses.</p>	Radionuclide mixture based on air sampling data.
Iodine uptakes	Assumes that stable iodine was not taken by population	Assumes that stable iodine was not taken by population
Ingestion of drinking water (L/d)	<p>Adult: 2</p> <p>Child 10 years: 1</p> <p>Child 1 year: 0.75</p> <p>Infant 6 months: 1.2 This group was added to consider ingestion of formula milk prepared with tap water</p> <p>Assumes restrictions on water consumptions were not followed.</p>	<p>Humanitarian: 6</p> <p>Adults and Children: 0.2 to 4 depends on age and physical activity level</p> <p>Assumes base populations consumed water from municipal water supplies.</p>
Ingestion of food	<p>Considered with many conservative assumptions and several scenarios. Excludes modeling of imposition of food restrictions. WHO expert panel put a significant emphasis on this pathway as its assessment was for the general public who consumed food on the market.</p> <p>For several categories/locations, this pathway constituted a relatively significant component of the dose.</p> <p>Many assumptions were recognized by the authors as extreme, “absolute upper bound of the dietary exposure.”</p>	<p>Considers most personnel consumed food from military supplies obtained primarily from the United States and did not consume contaminated food.</p> <p>Assumes most DOD-affiliated individuals who ate small amounts of food from local supplies would have received a relatively small dose.</p> <p>Recommends a case-by-case evaluation for persons who report having consumed food from non-DOD sources.</p> <p>Includes a reference of the WHO assessment of food ingestion and a sample dose estimate for those who did consume food on the market.</p>



Characteristic/ Parameter	World Health Organization (WHO)	Department of Defense (DOD)
Ingestion of soil and dust (incidental) (mg/day)	Considered insignificant	Humanitarian: 500 Adult: 17 to 200 Children (1–15 years): 17 to 1000 Infant: 17 to 1000 Depends on physical activity level for each age group. Soil activity was measured and ingestion doses were calculated. Results show that there were negligible dose contributions from soil and dust ingestion.



**Table 2. Summary comparison of WHO and DOD doses**

Characteristic/ Parameter	World Health Organization (WHO)	Department of Defense (DOD)
Locations included	Neighboring prefectures: Chiba, Gunma, Ibaraki, Miyagi and Tochigi.  Rest of Japan: Entire country excluding Fukushima and neighboring prefectures listed above.	<u>Humanitarian/Adults<sup>(*)</sup></u> : Sendai Airport (Miyagi), City of Ishinomaki (Miyagi), City of Yamagata (Yamagata), City of Oyama (Tochigi), Hyakuri AB (Ibaraki), Yokota AB (Tokyo), Akasaka Press Center (Tokyo), Atsugi NAF (Kanagawa), Yokosuka NB (Kanagawa), and Camp Fuji (Shizuoka).  <u>Children<sup>(*)</sup></u> : Hyakuri AB (Ibaraki), Yokota AB (Tokyo), Akasaka Press Center (Tokyo), Atsugi NAF (Kanagawa), Yokosuka NB (Kanagawa), and Camp Fuji (Shizuoka) .  <u>Note<sup>(*)</sup></u> : Doses for cohorts at Misawa AB (Aomori), Iwakuni MCAS (Yamaguchi), Sasebo NB (Nagasaki) are very low and are excluded from the results below.  <sup>(*)</sup> AB=Air Base, NAF=Naval Air Field, NB=Naval Base, MCAS=Marine Corps Air Station.
Doses inside Japan (total effective dose)	For adults, and 10- and 1-year-old children, the ranges are the same: 0.01–1 rem (0.1 to 10 mSv) (neighboring prefectures) 0.01–0.1 rem (0.1 to 1 mSv) (rest of Japan)	Following doses are for highest physical activity and no time spent indoors: Humanitarian/adults: 0.036–0.12 rem (0.36 to 1.2 mSv) Children (0–17 years): 0.044–0.16 rem (0.44 to 1.6 mSv)
Doses inside Japan (total equivalent dose to the thyroid)	For adults, and 10- and 1-year-old children, the ranges are the same: 0.1–1 rem (1 to 10 mSv) (neighboring prefectures) 0.1–1 rem (1 to 10 mSv) (rest of Japan)	Following doses for highest physical activity and no time spent indoors: Humanitarian/adults: 0.44–1.2 rem (4.4 to 12 mSv) Children (0–17 years): 0.5–2.7 rem (5 to 27 mSv)
Uncertainty Analysis	A qualitative discussion of the main sources of uncertainty in the dose estimates is included in the report.  The WHO International Expert Panel noted: a quantitative uncertainty analysis has not been possible due to the early nature of the study and the lack of statistical input distributions. As a result of the cautious approaches used, the panel considers the assessment to be as robust as possible at the time of publication.	A separate probabilistic analysis of uncertainties is being performed to assess whether the estimated doses are higher than the 95 <sup>th</sup> percentile of the probabilistic total dose distributions.  Preliminary results for four key DOD cohorts and locations show that the doses estimated by DARWG are higher than 95 <sup>th</sup> percentile of the dose distributions.